Theoretical Overview

Probing the Nucleon's Spin Structure with Longitudinally Polarized Beams

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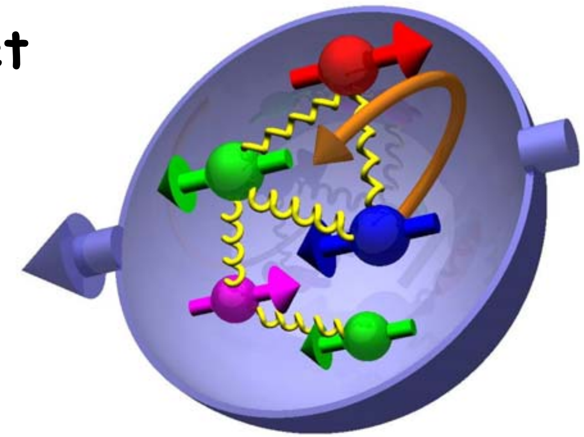
RIKEN

main objective with long. polarization

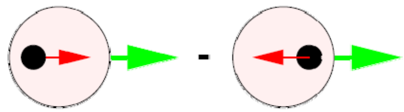
- we want to understand the nucleon's spin budget in terms of
  - total spin polarizations $\int \Delta f(x,\mu)\, dx$
  - orbital angular momenta

  of quarks and gluons



- to achieve this goal we have to extract the fully x-dependent helicity parton densities $\Delta f(x,\mu)$ from experiment

$$\boxed{\Delta f(x) \equiv f_{+}^{N_+}(x) - f_{-}^{N_+}(x)}$$



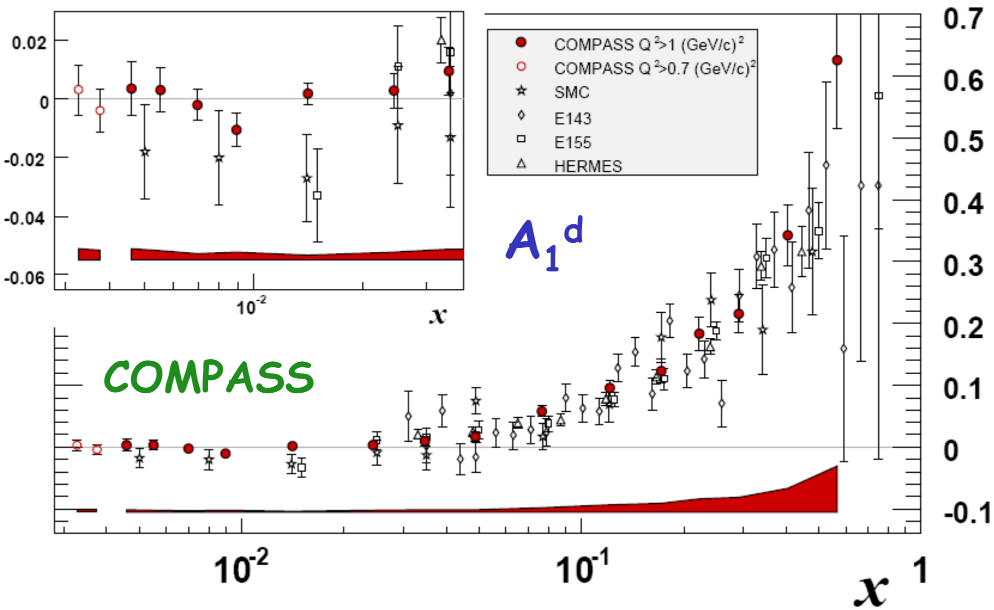
important test of QCD:
- understanding of hadron structure
- hard scattering QCD dynamics
- factorization & universality

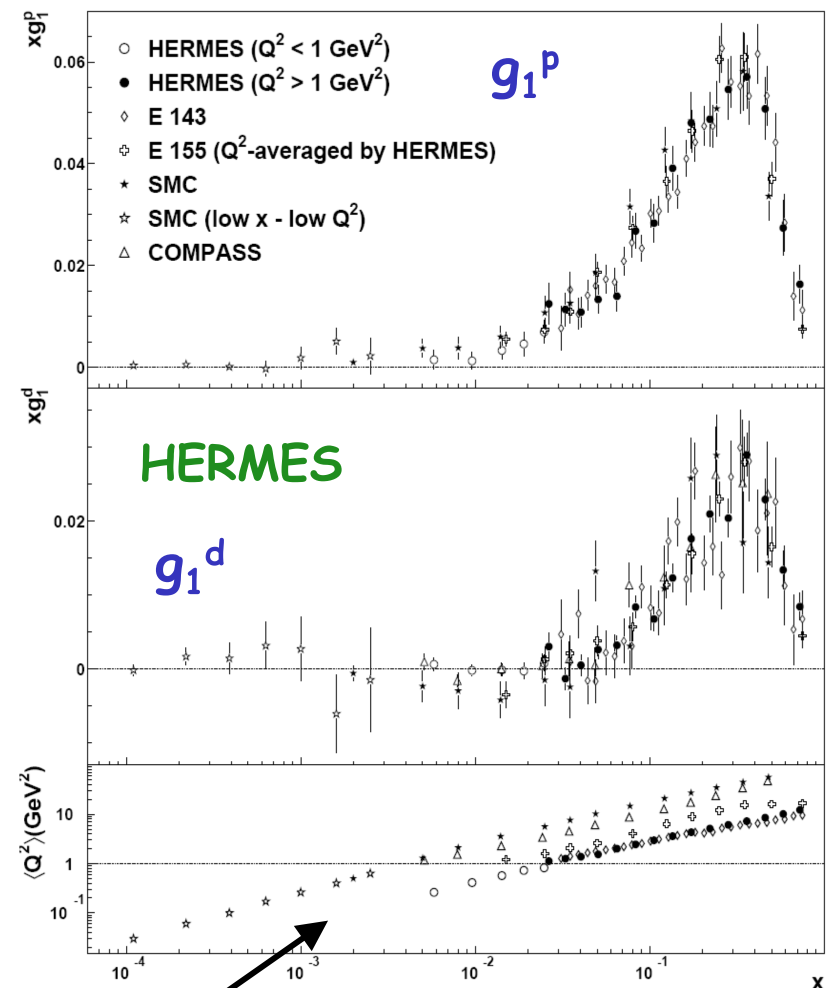
standard tool: polarized DIS

more than 25 years of beautiful data on polarized DIS – still progress!

in 2006/07:

- final DIS results from HERMES
- deuteron results from COMPASS



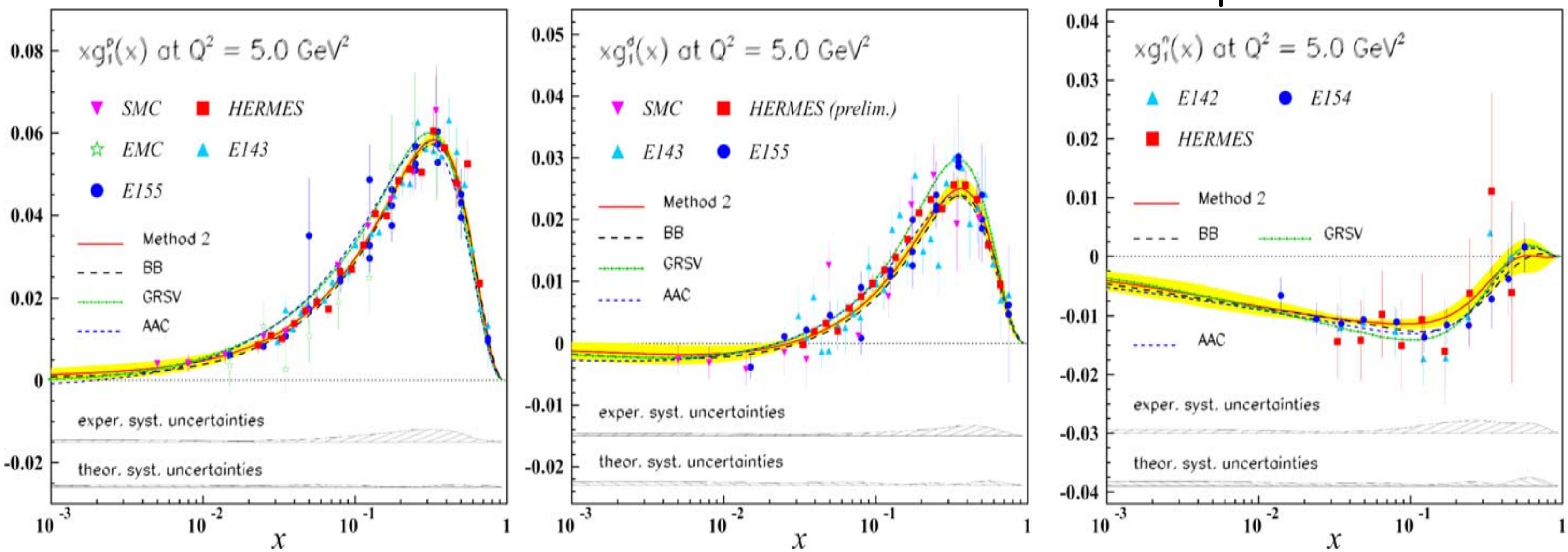


limited x,Q^2 coverage

NLO QCD analysis of polarized DIS

find: very good agreement with data at NLO level

example: Blümlein & Böttcher



acronyms:

AAC: Asymmetry Analysis Collaboration (Hirai, Kumano, Saito)

BB: Blümlein & Böttcher

GRSV: Glück, Reya, MS, Vogelsang

salient features:

- quark contr. to $S_z^p = 1/2$: $\Delta\Sigma \simeq 0.2 \div 0.3$
- gluon largely unconstrained due to limited (x,Q^2) coverage $\rightarrow$ eRHIC!

while waiting for a first polarized ep-collider

Δg can be further constrained

in pp-collisions at RHIC...

milestone of RHIC spin program

(as far as possible) a model independent determination of

Collins, Soper; Manohar

$$\Delta g(x,\mu) = \frac{1}{4\pi x P^+} \int dy^- e^{iy^- xP^+} \langle P,S | F_a^{+j}(0,y^-,\vec{0}) \mathcal{F} \tilde{F}_{+j}(0) | P,S \rangle \Big|_\mu$$

gauge link

features:

- interpretation as diff. of number operators only in $A^+=0$ gauge

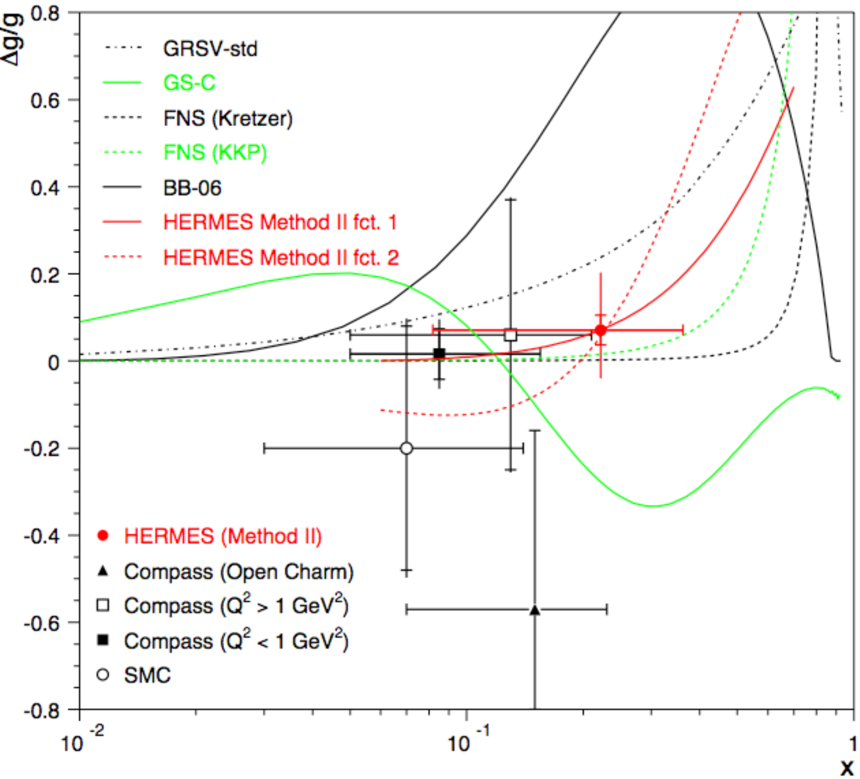
- all $n \geq 2$ moments, $\int x^{n-1} \ldots dx$, give local operators but there is **no** gauge-invariant local gluonic operator for $n=1$

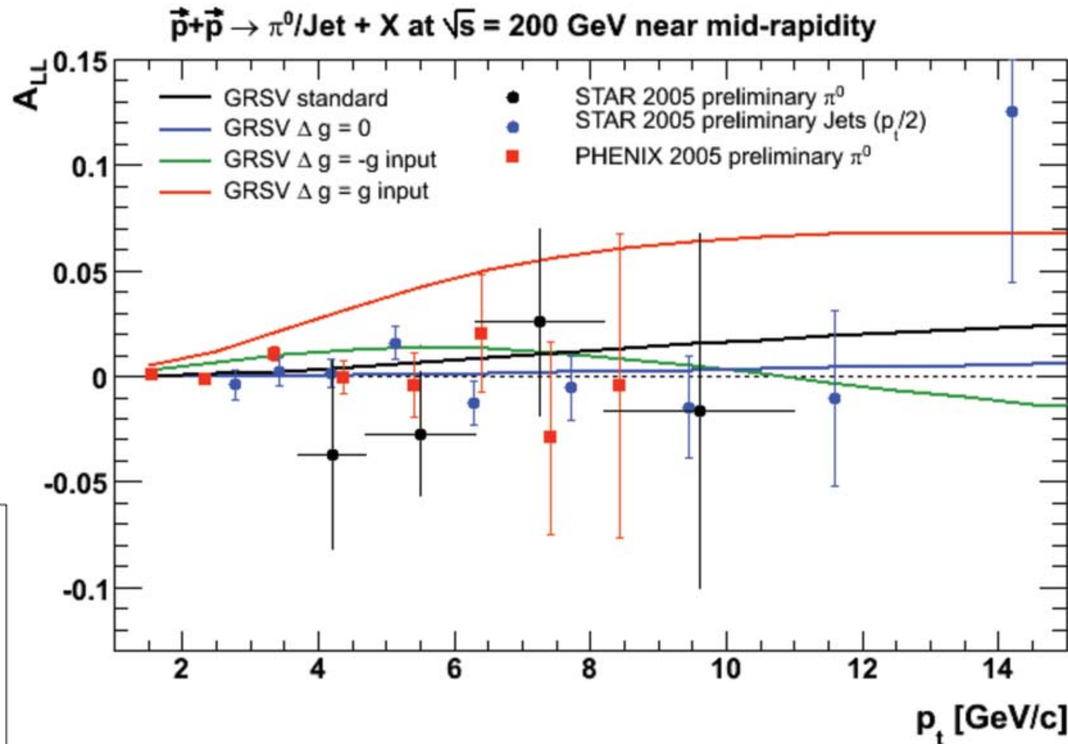
- in $A^+=0$ gauge the **1st moment** also collapses into a local operator and has the interpretation as **gluon contribution to the spin "sum rule"**

data probing Δg are rolling in now ...

pp: PHENIX, STAR

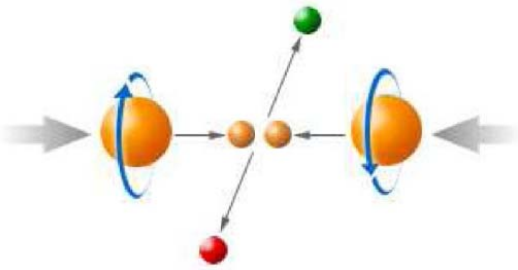
lp: HERMES, COMPASS, SMC





- What do they imply?
- How to analyze them properly?
- Potential problems & limitations?

hunting down the elusive Δg



outline:

- theoretical framework
- extracting Δg: results & complications

■ the general strategy is simple ...

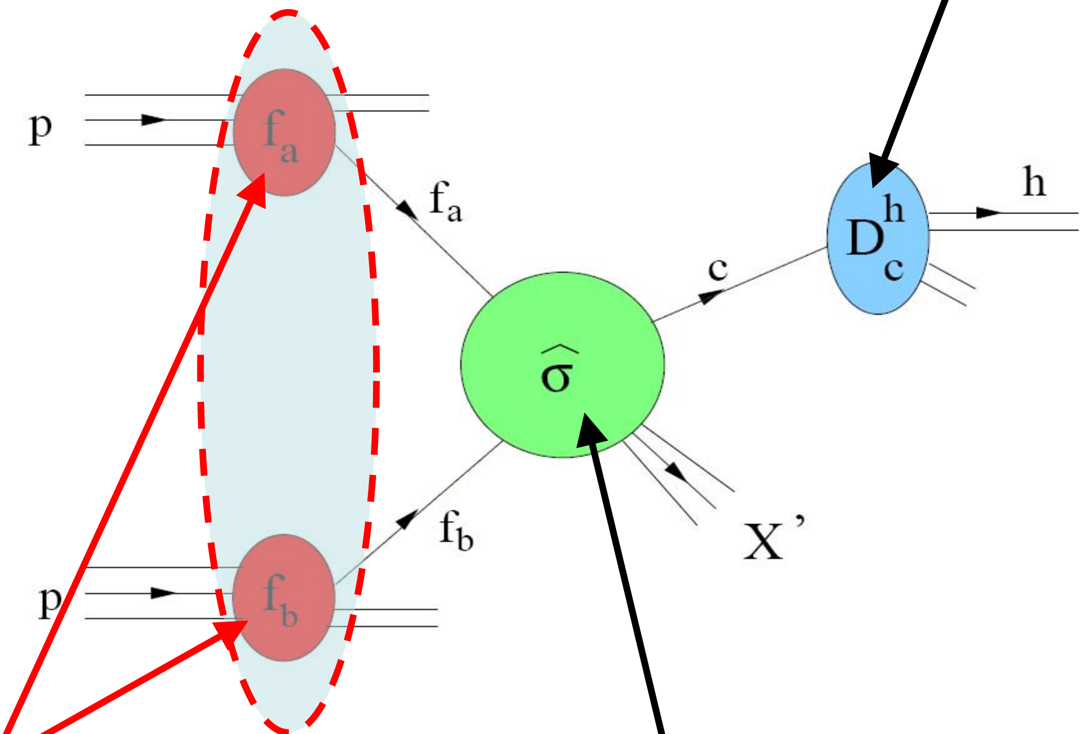
e.g. $pp \to \pi X$:

new

from global analysis

measure!

$$d(\Delta)\sigma \simeq$$



learn about
hadronic/spin structure

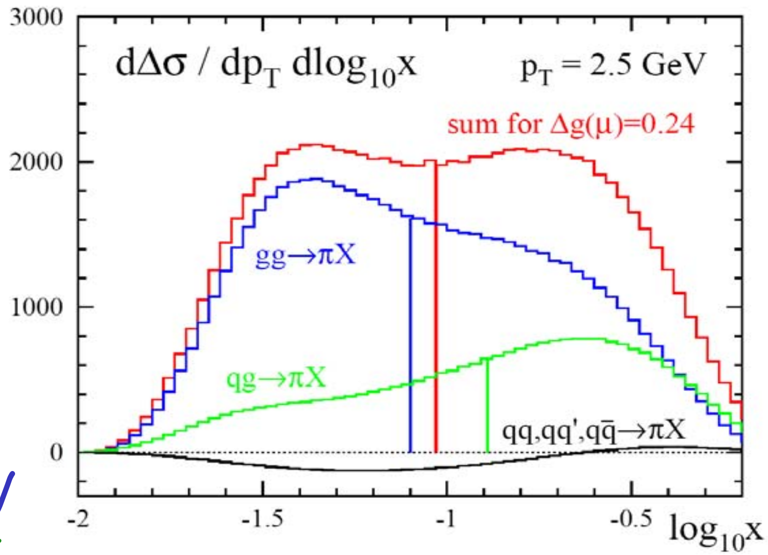
compute as a power series in α_s in pQCD

… but it is an intricate problem:

recall

$$\frac{d\sigma^{pp\to\pi X}}{dp_T d\eta} = \sum_{abc} \int dx_a\, dx_b\, dz_c\, f_a(x_a,\mu_f)\, f_b(x_b,\mu_f)\, D_c^{\pi}(z_c,\mu_f') \times \frac{d\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^{\pi}/z_c, \mu_f, \mu_f', \mu_r) + \mathcal{O}\left(\frac{\lambda}{p_T}\right)^n$$

- information on long-distance physics inside **complicated convolutions** & summed over **many partonic subprocesses**
  - no 1:1 correspondence between data and parton densities or frag. fcts.
  - information on momentum fractions "smeared" over significant range



ex.: $pp \to \pi X$ at $p_T = 2.5$ GeV
$\overline{\text{MS}}$

theoretical calculations depend on unphysical scales

- a *measurable* cross section $d(\Delta)\sigma$ has to be *independent* of μ_r and μ_f

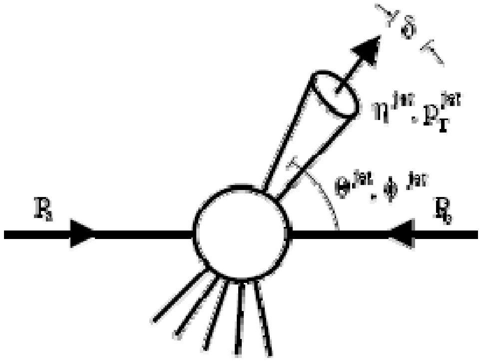
$$\frac{d(\Delta)\sigma}{d\ln\mu_{r,f}} = 0 \quad \Longrightarrow$$ leads to renormalization group eqs. like, e.g., DGLAP evolution

- if we truncate the series after the first N terms, there will be a *residual scale dependence* of order (N+1) $\rightarrow$ theory error

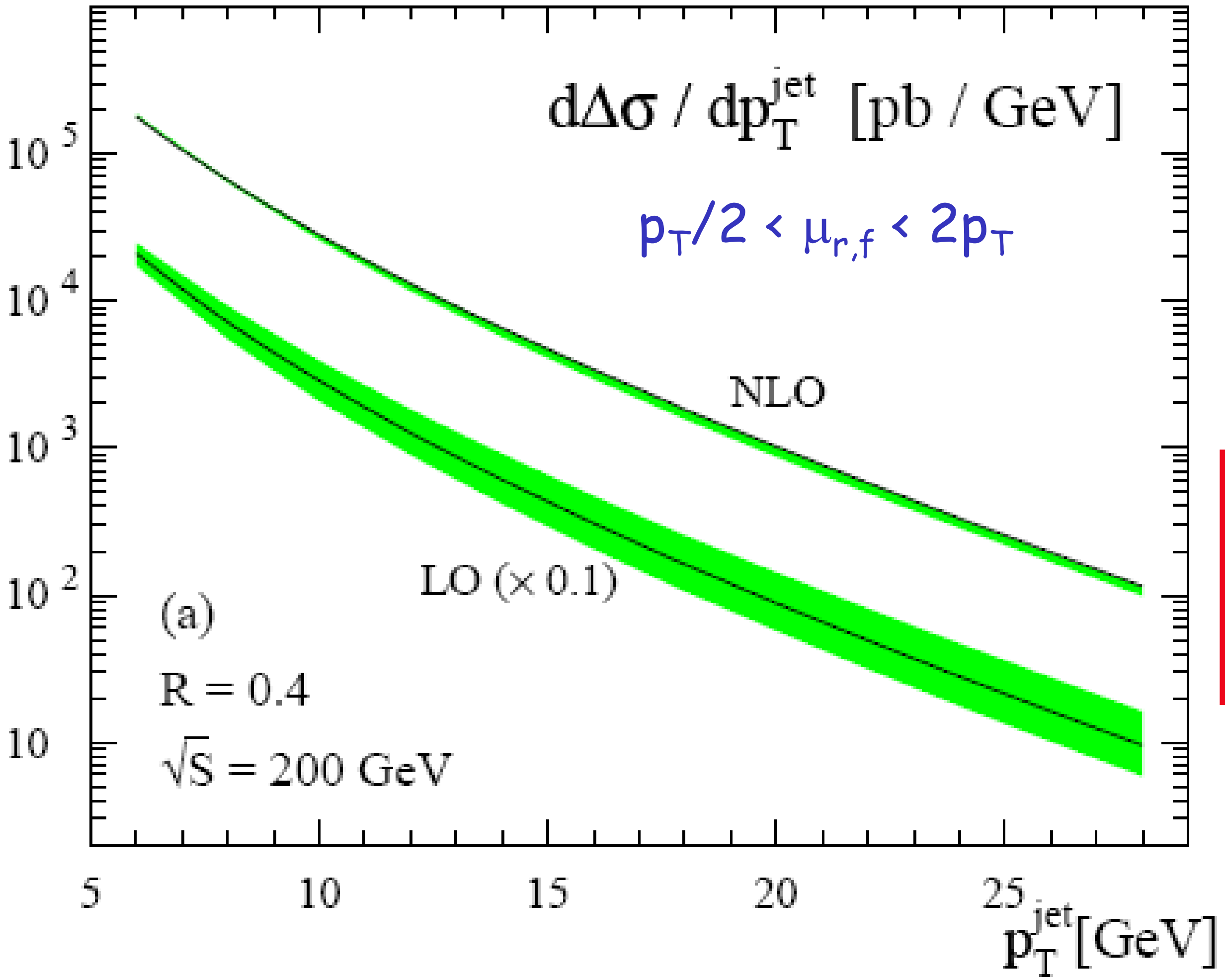
- there is no such thing like "the right scale" (not even μ=Q in DIS)

> the harder we work, the less the final result
> should depend on these artificial scales
>
> **a powerful gauge of the reliability of a pQCD calculation**

example: single-jet production at RHIC



taken from B. Jäger, MS, W. Vogelsang



going beyond the LO is a must for *any* quantitative study

going beyond the LO is in every aspect a major enterprise

LO NLO NNLO

$$d\hat{\sigma} = d\hat{\sigma}^{(0)} + \alpha_s d\hat{\sigma}^{(1)} + \alpha_s^2 d\hat{\sigma}^{(2)} + \ldots$$

number of final-state partons

complexity of calculation

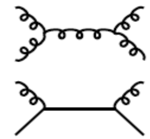
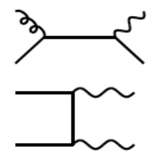
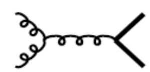
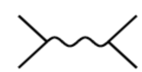
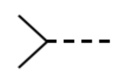
rough estimate

start of precision physics

... pushes math. tools & computer algebra to their limits

tremendous progress on NLO calculations for RHIC-spin

available:

	Reaction	Dom. partonic process	probes	LO Feynman diagram	
hadrons	$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg		Jäger,Schäfer, MS, Vogelsang; de Florian
jets	$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)	Jäger,MS,Vogelsang; Signer et al.
photons	$\vec{p}\vec{p} \to \gamma + X$ $\vec{p}\vec{p} \to \gamma + \mathrm{jet} + X$ $\vec{p}\vec{p} \to \gamma\gamma + X$ [67, 73, 74, 75, 76]	$\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{g} \to \gamma q$ $\vec{q}\vec{\bar{q}} \to \gamma\gamma$	Δg Δg $\Delta q, \Delta\bar{q}$		Gordon,Vogelsang; Contogouris et al.; Gordon, Coriano
heavy flavors	$\vec{p}\vec{p} \to DX, BX$ [77]	$\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$	Δg		Bojak, MS
	$\vec{p}\vec{p} \to \mu^+\mu^- X$ (Drell-Yan) [78, 79, 80]	$\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$	$\Delta q, \Delta\bar{q}$		
Drell Yan	$\vec{p}\vec{p} \to (Z^0, W^\pm)X$ $p\vec{p} \to (Z^0, W^\pm)X$ [78]	$\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}\,'\vec{\bar{q}} \to W^\pm$ $\vec{q}\,'\bar{q} \to W^\pm,\ q'\vec{\bar{q}} \to W^\pm$	$\Delta q, \Delta\bar{q}$		Weber; Gehrmann; Kamal; Smith et al.

work in progress: particle-correlations for RHIC
(hadron-hadron, hadron-photon, heavy-flavor)

new

Jäger, Owens, MS, Vogelsang; Riedl, MS

strength of RHIC: unpolarized "benchmarks"

pQCD challenged by experiment

find (jets, pions, photons, …)

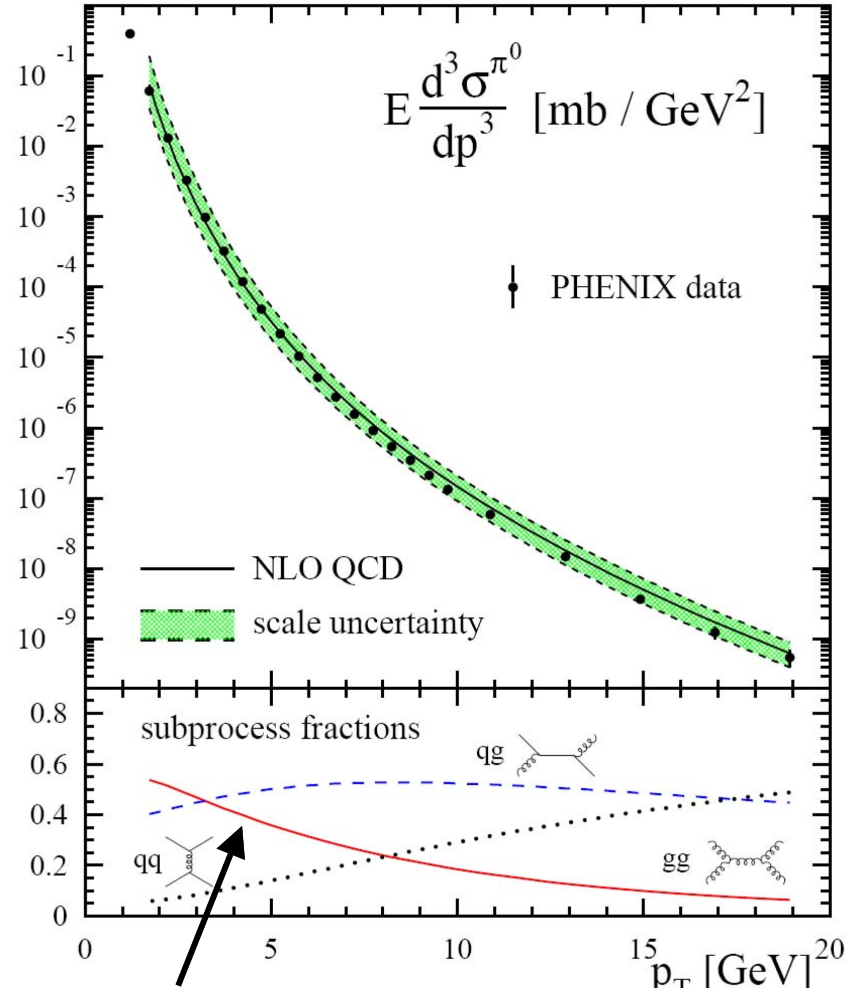
perfect agreement over many orders of magnitude

foundation/baseline for:

- polarized pp collisions at RHIC
- interpretation of heavy-ion results

much less clear at fixed-target exp.

latest from RHIC (arXiv:0704.3599)
vs. NLO pQCD Jäger, MS, Vogelsang



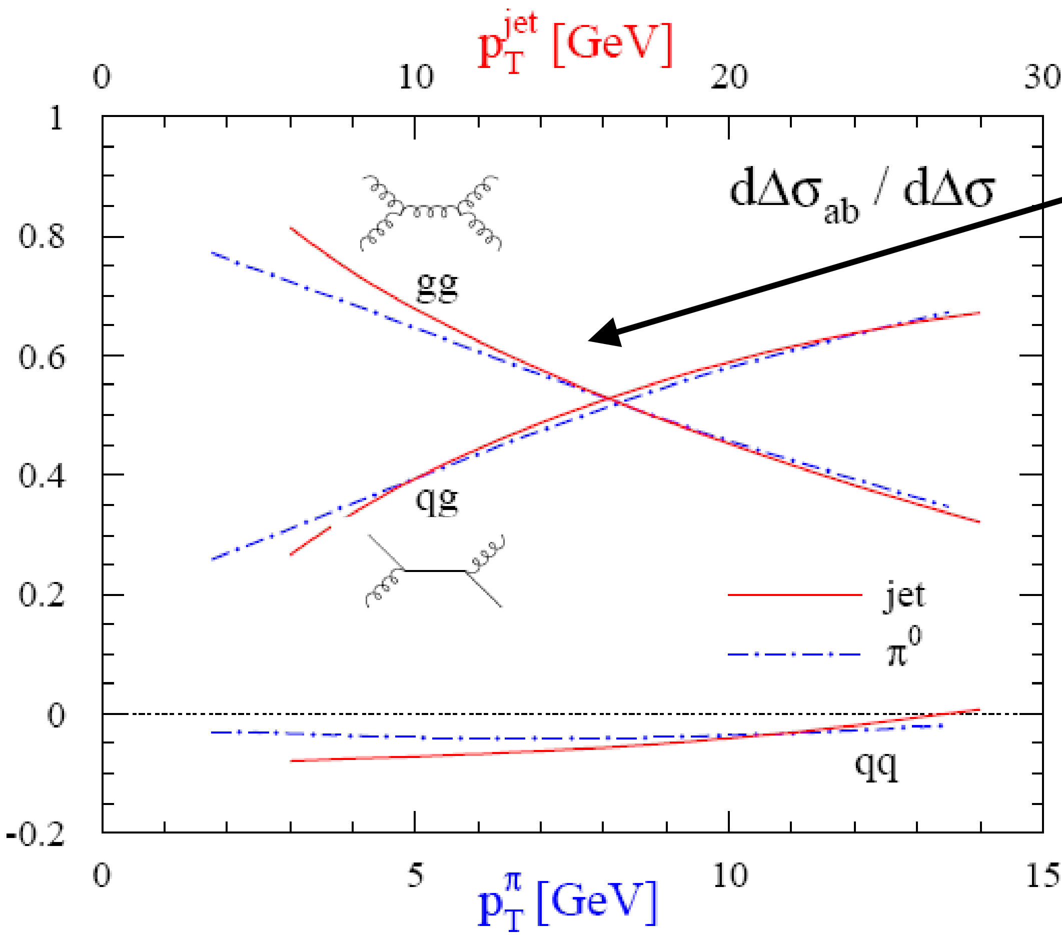
gluons are key players

what do RHIC data already tell us?

current probes at RHIC: single-inclusive hadrons & jets at moderate p_T and mid-rapidity η

PHENIX, STAR

relevance of different subprocesses:

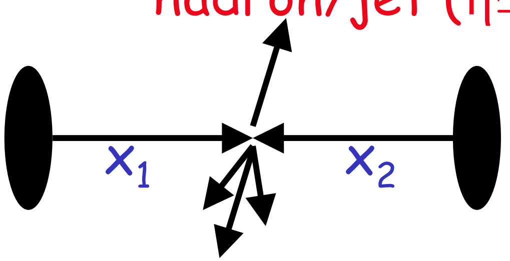


(taken from Jäger,MS,Vogelsang)

✓ gluon-induced processes dominant

→ **sensitivity to Δg**

but at central rapidities

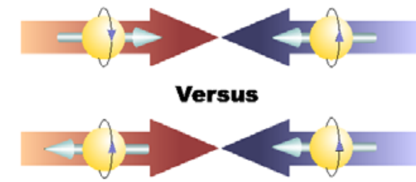


→ probe $\Delta g(x_1)\,\Delta g(x_2 \simeq x_1)$

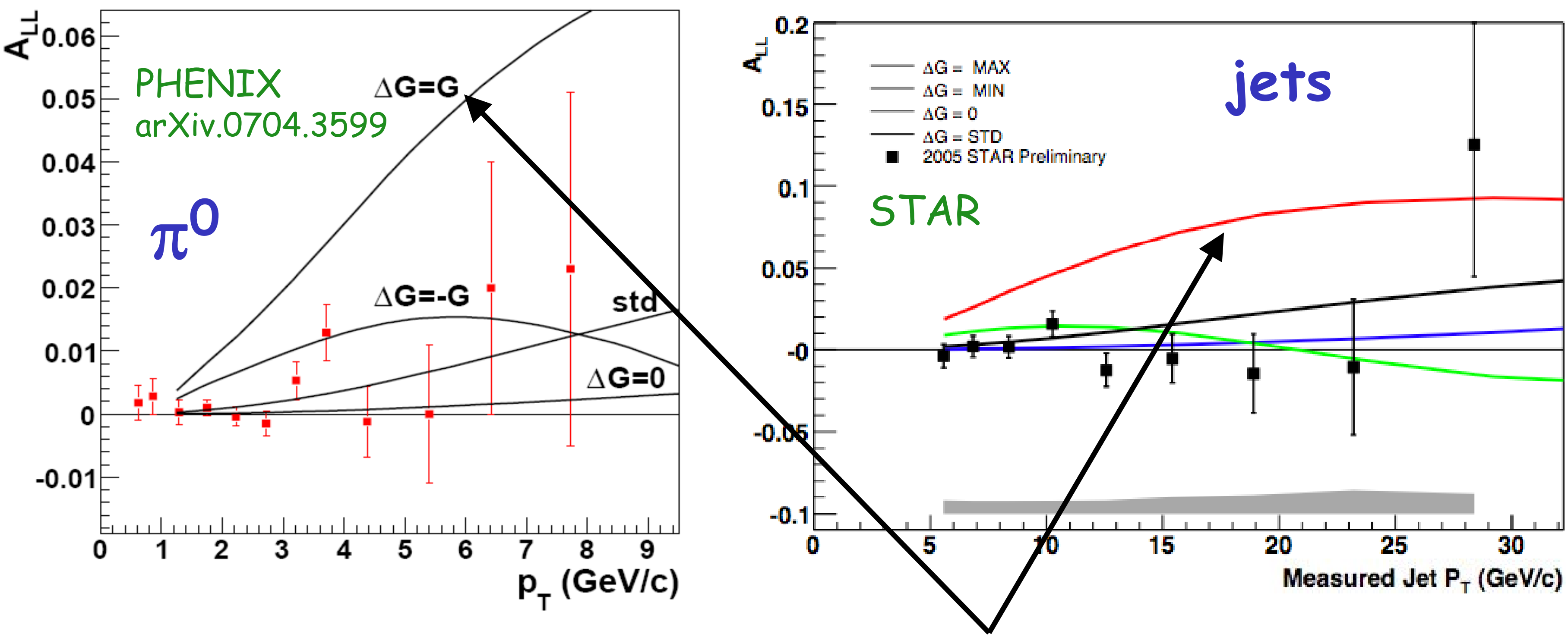
"sign deadlock"

indeed …

spin asymmetry A_{LL}



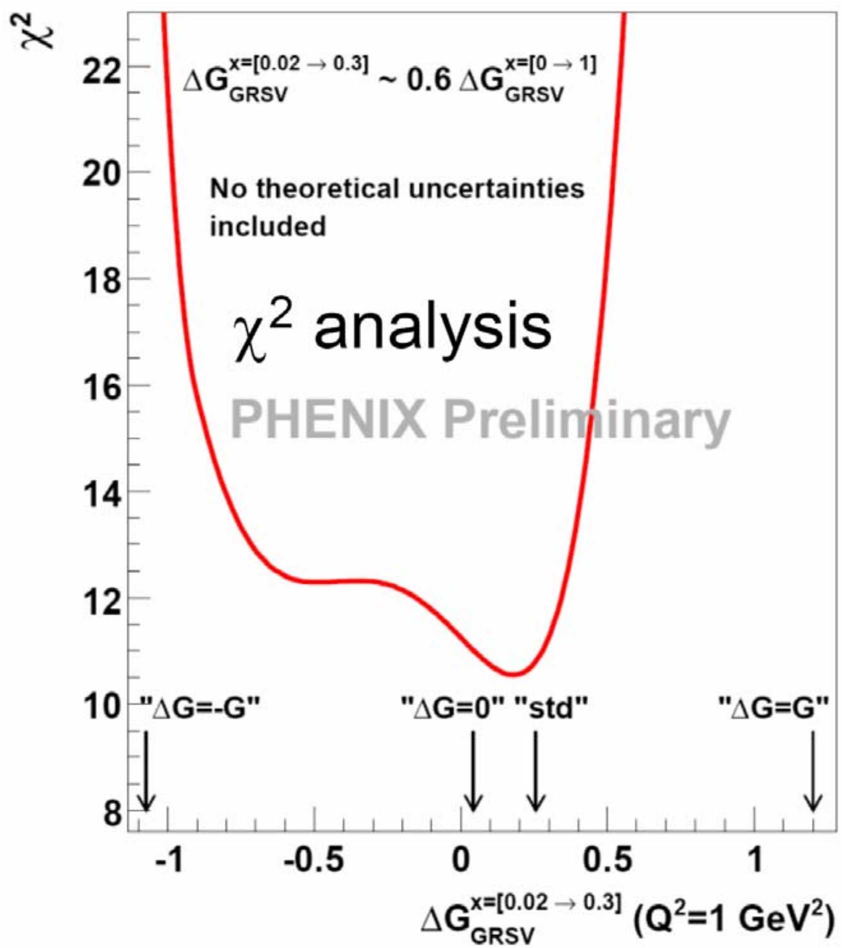
single-incl. A_{LL} vs. NLO calc. for very diff. gluon polarizations Δg

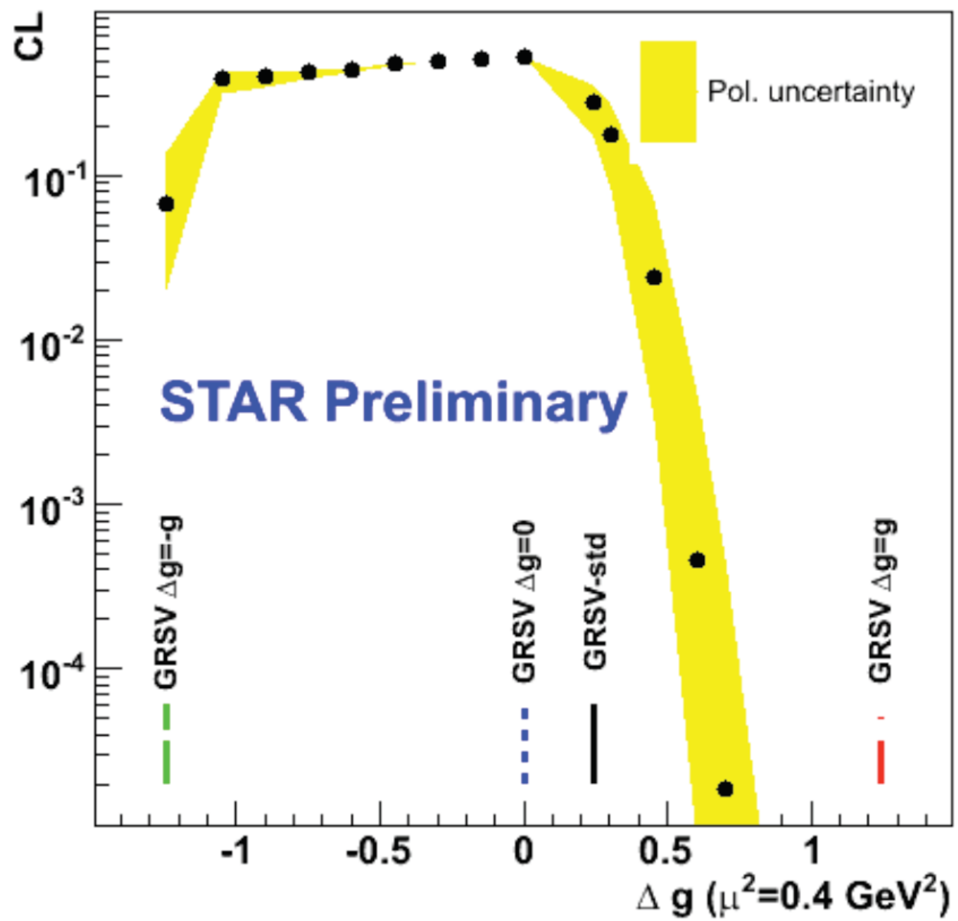


- **major result:** very large ($\gtrsim$ 2 units of $\hbar$) "anomaly-inspired" Δg dead

but beyond that ??

experiments now do their own theory analysis …





Q: how robust are these results?

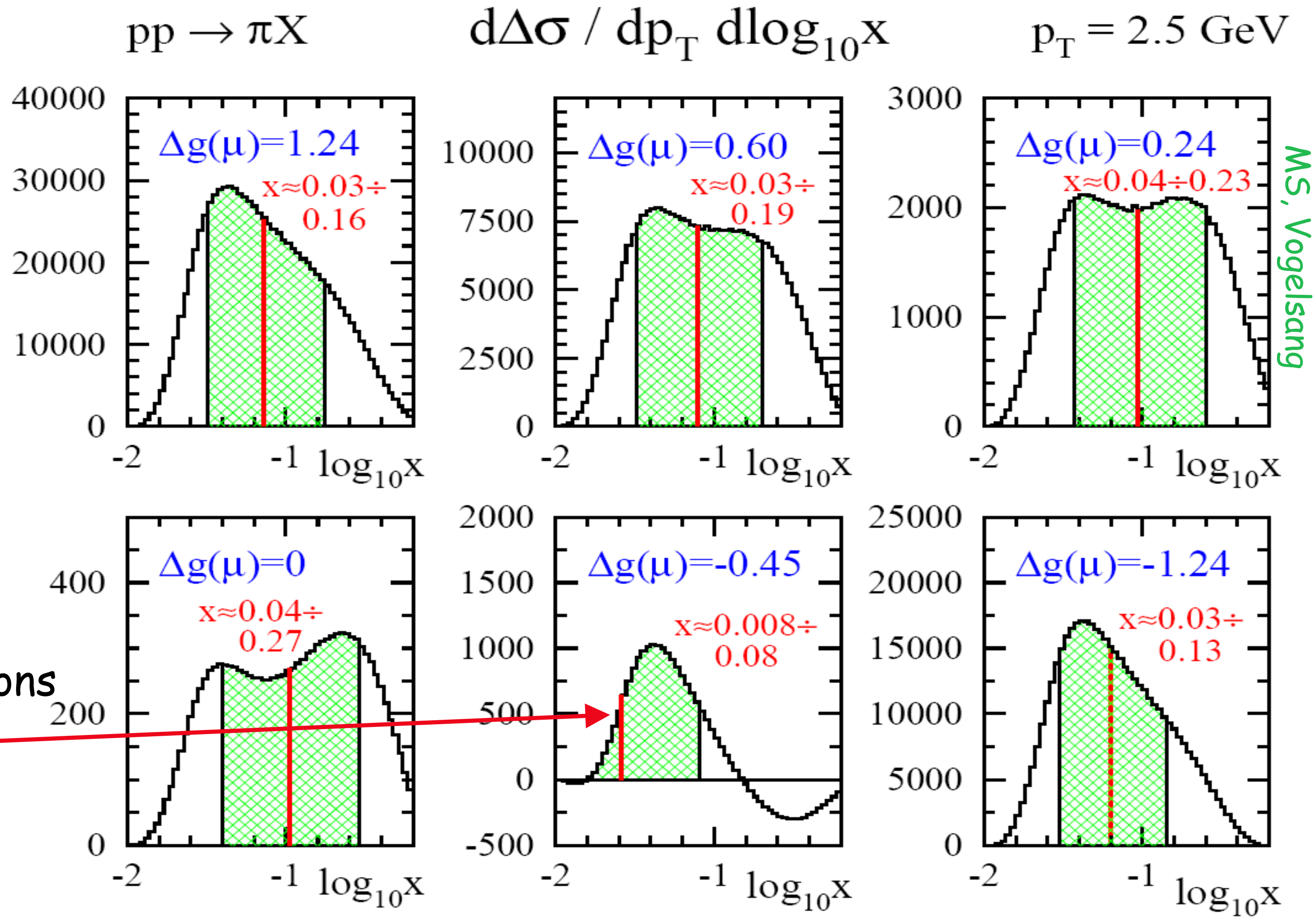
[heavily biased by GRSV framework? ; x-range? ; 1st moment? ; …]

data ↔ x-range probed

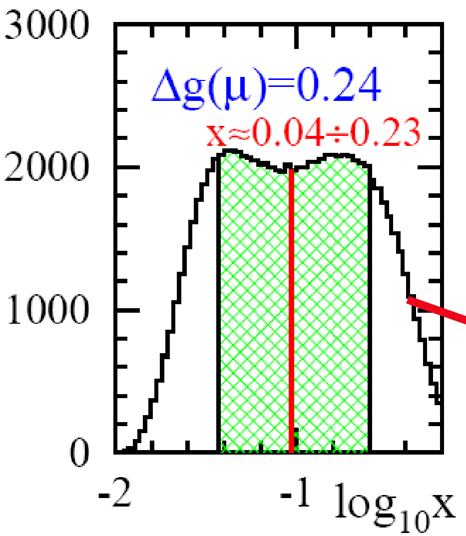
can we figure out which $\langle x \rangle$ is probed? **difficult!**

example:

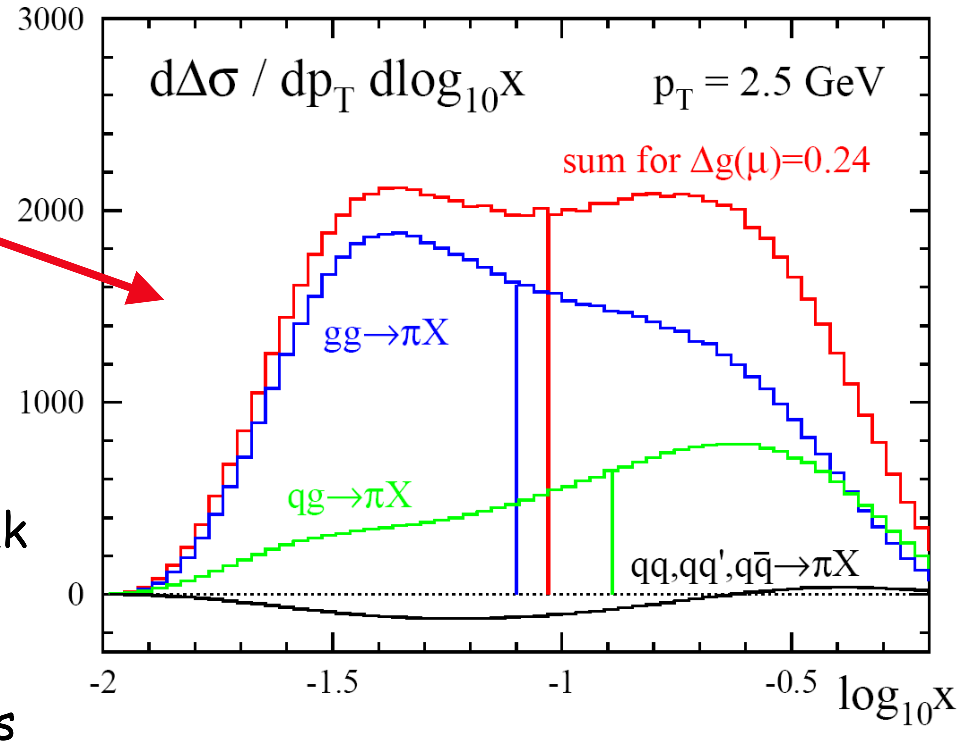
- x-range spreads out significantly
- depends on *unknown* Δg
- complication: possible oscillations obscure $\langle x \rangle$



a closer look for GRSV "standard"



diff. subprocesses populate different x-ranges



gg vs. qg interplay explains all:

- large pos. Δg $\rightarrow$ pronounced *gg* peak
- small pos. Δg $\rightarrow$ double peak
- not too large neg. Δg $\rightarrow$ oscillations

estimates of $x \pm dx$ very difficult w/o knowing Δg

→ important disclaimer

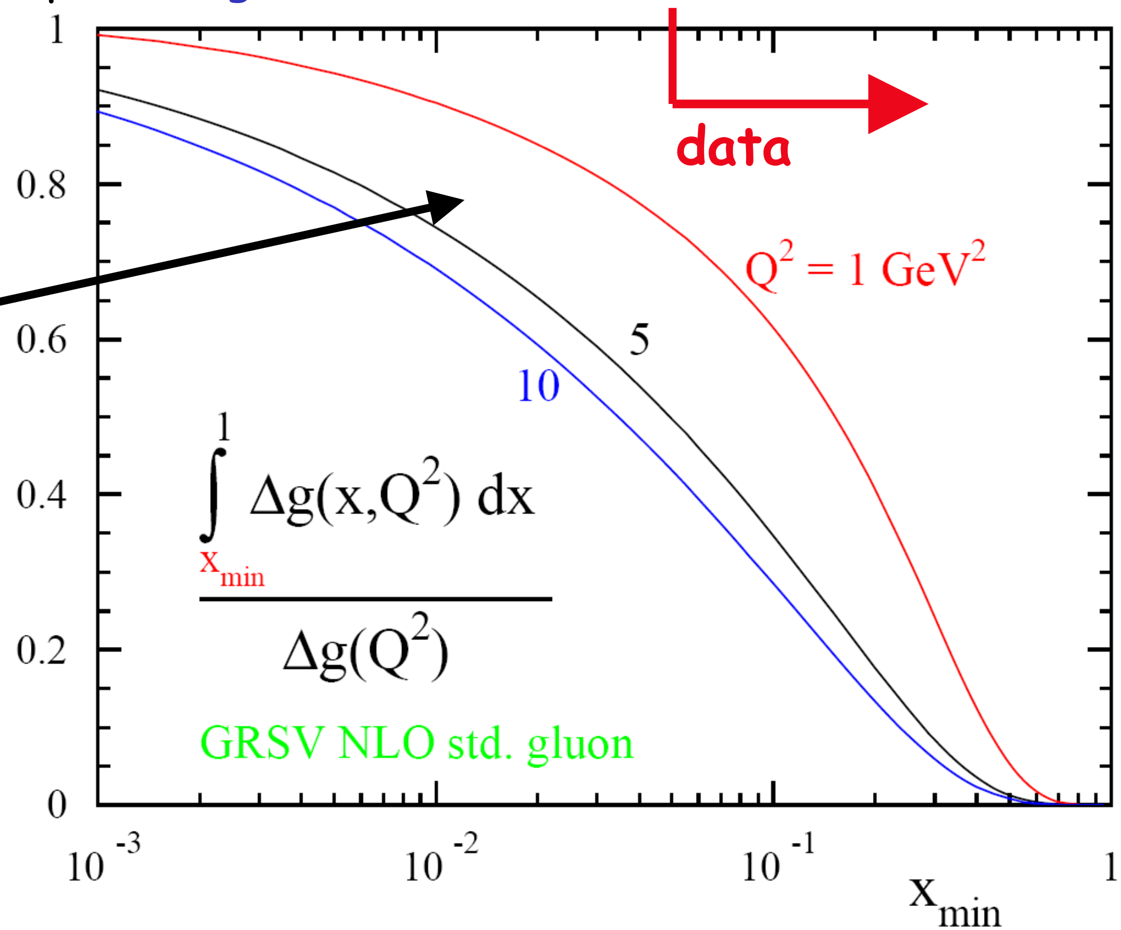
RHIC data so far are sensitive to a rather limited x-range $0.04 \lesssim x \lesssim 0.2$

→ full moment $\int_0^1 dx\, \Delta g(x,\mu)$ still a long shot

(i.e., depends on *assumed* shape for Δg)

small values of x can be crucial for 1st moment !!

need a much more precise "x-mapping"



[also Gehrmann-Stirling gluons pick up a large small-x contribution!!]

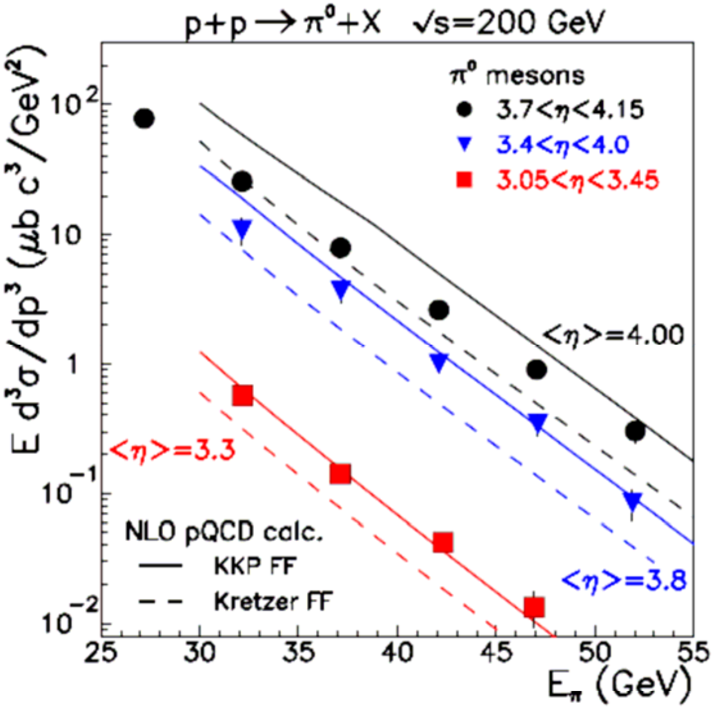
other issues to worry about …

how do quarks & gluons hadronize?

key phenomenological input for all calculations of meson/baryon production

plenty of experimental information but we know much less about hadronization than about hadron structure - why?

many short-comings of available models revealed by RHIC data, e.g.:



NLO calc.: Jäger, Schäfer, MS, Vogelsang

- general trend: "Kretzer" below data (STAR, PHENIX, BRAHMS)
- no reliable charge/flavor separation (STAR, BRAHMS: π^+ vs. π^- yields, …)

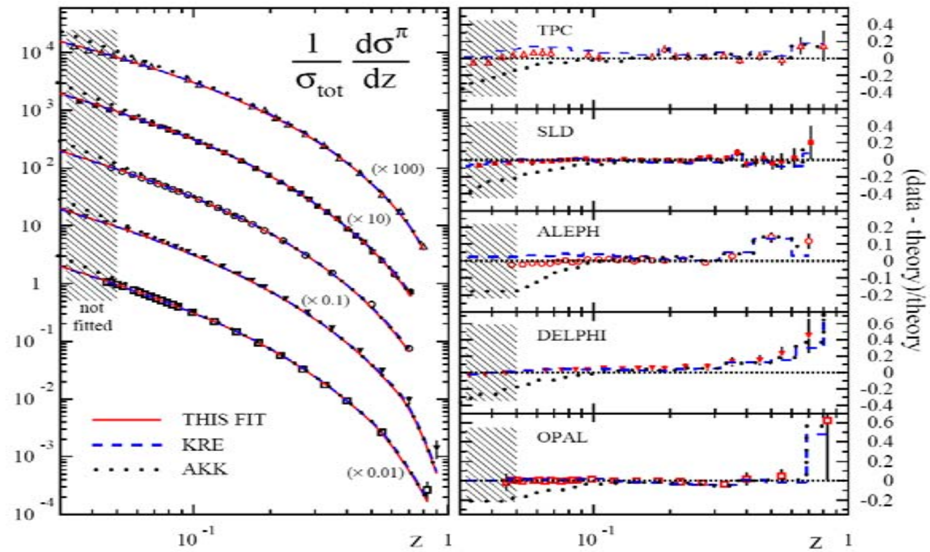
we must do better!

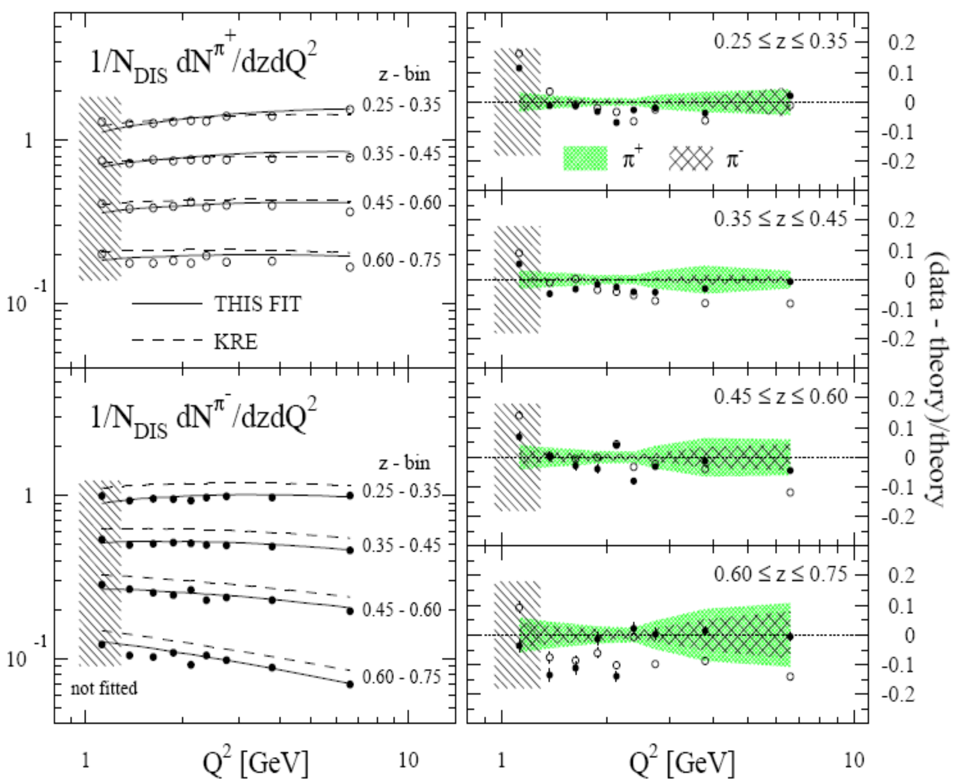
1st global analysis of e^+e^- *and* ep, pp data

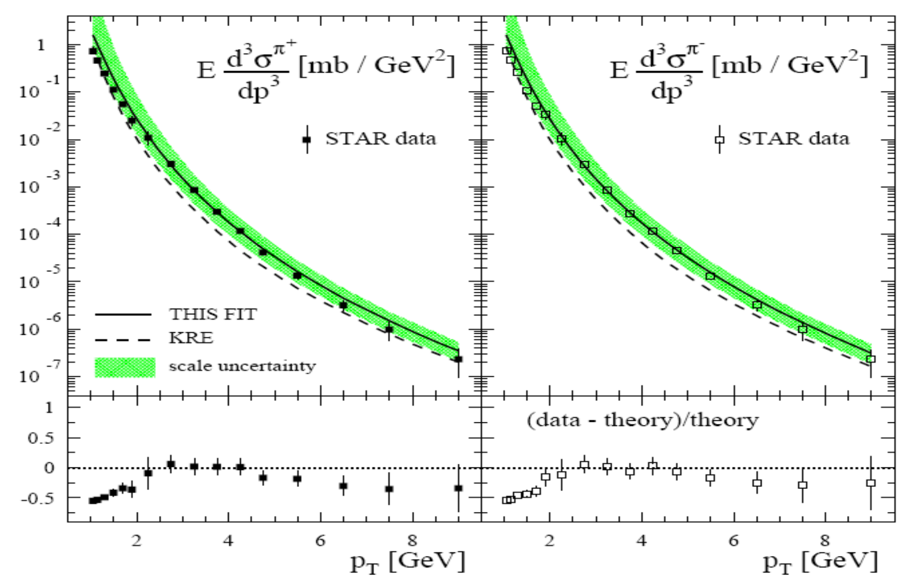
de Florian, Sassot, MS: **hep-ph/0703242** (PRD) → more on Wednesday

<u>main features:</u>

- handle on gluon fragmentation
- flavor separation
- uncertainties via Lagrange multipl.
- describes all current data

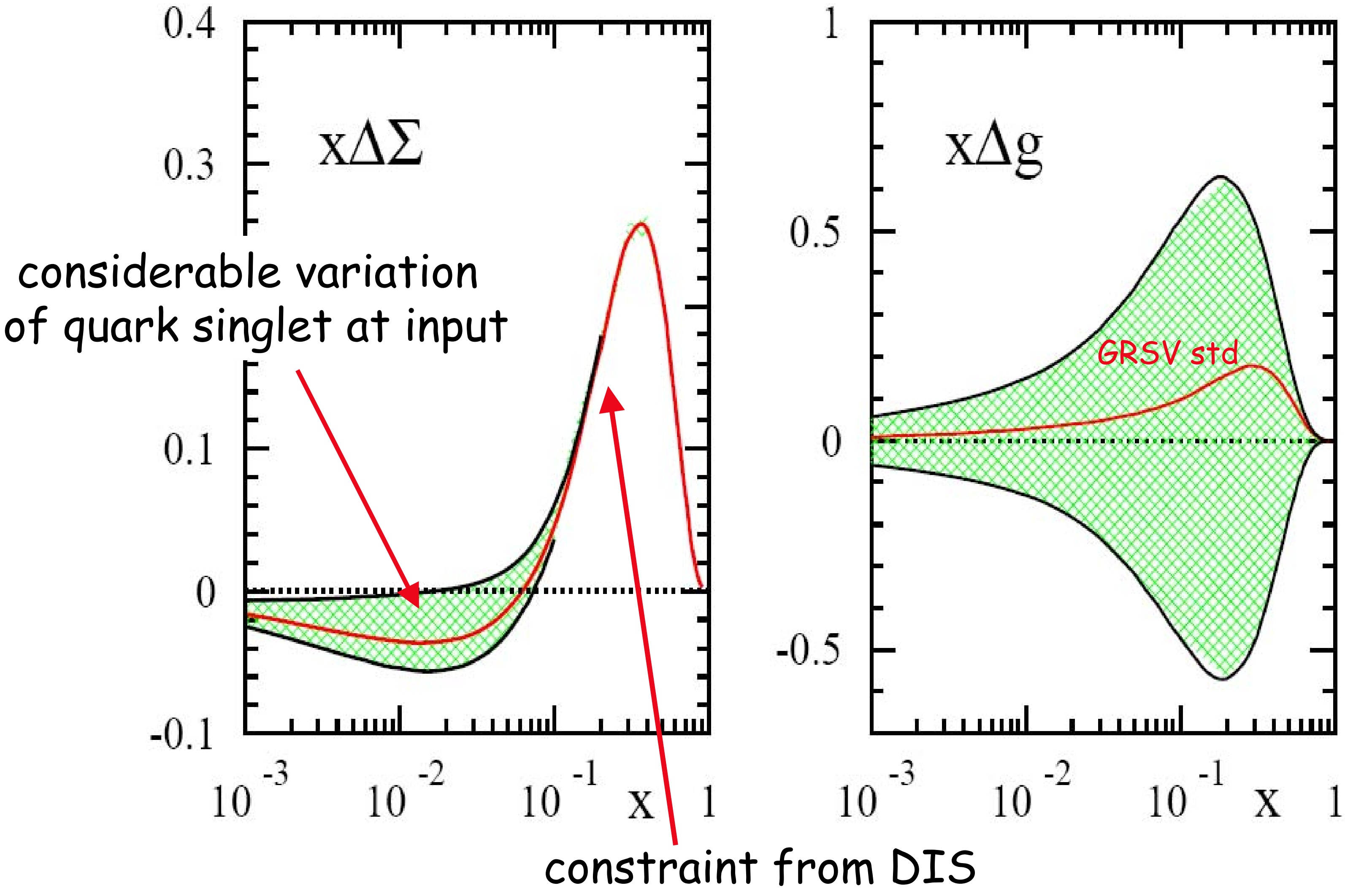






■ can one assume that $\Delta\Sigma$ is known?

NO, it is misleading to extract *only* Δg w/o refitting the quarks:



can I use MCs to extract Δg ?

Δg **extraction through signal/background separation based on MC**

e.g., $lp \to HX$ $\quad A_{LL} = \frac{\sum \Delta f \otimes d\Delta\hat{\sigma} \otimes D_c}{\sum f \otimes d\hat{\sigma} \otimes D_c} \rightarrow \frac{\sigma_{\gamma g}}{\sigma_{tot}} \frac{\Delta g}{g} \frac{\Delta\hat{\sigma}_{\gamma g}}{\hat{\sigma}_{\gamma g}} + A_{LL}^{\text{backgr.}}$

"fractions" from MC

MC crucial to model experiment but cannot replace a full global analysis:

- requires kind of "mean-value" theorem as $\frac{\Delta g \otimes d\Delta\hat{\sigma} \otimes D_c}{g \otimes d\hat{\sigma} \otimes D_c} \neq \frac{\sigma_{\gamma g}}{\sigma_{tot}} \frac{\Delta g}{g} \frac{\Delta\hat{\sigma}_{\gamma g}}{\hat{\sigma}_{\gamma g}}$
  (also note that $\langle \hat{A}_{\gamma g}(x) \rangle \neq \hat{A}_{\gamma g}(\langle x \rangle)$)
- MC hadronization not compatible with collinear pQCD which *defines* pdfs
- MC neither LO nor NLO (parton showers, ...)

$\boxed{\text{in general, expect: } \Delta g(\text{MC}) \neq \Delta g(\text{NLO pQCD analysis})}$

$\approx$ 20 years of experience in analyzing unpolarized data:

DFLM, … , GRV, MT, MRS, … , MSTW, CTEQ, …

learning about nucleon structure requires a global QCD analysis

even more true for the spin structure

due to lack of "HERA-like" DIS data

but current data are not yet sufficient, e.g.:

- quark & anti-quark flavor separation $\rightarrow$ W-physics @ 500 GeV
- gluon polarization (sign, small x, …)

some future avenues for Δg at RHIC

Δg: where do we stand now?

1988 $\int \Delta g\, dx$ thought to be large: **2-4 $\hbar$** Altarelli, Ross; ...
in the aftermath of the EMC result
due to axial anomaly (very controversial Jaffe; Ji; ...)

1995 "dark ages": several model calculations:

'95 Brodsky, Burkardt, Schmidt: $\Delta g(1\mathrm{GeV}) \approx 0.5\ \hbar$ (hel. retention, color coh.)

~ '97 Balitsky, Ji: $J_g(1\mathrm{GeV}) \approx 0.25$; expect $\Delta g < 0.5\ \hbar$ (QCD sum rules)

'98 Barone, Calarco, Drago: $\Delta g = 0.24\ \hbar$ (quark model)

2000 '00 Lee, Min, Park, Rho, Vento: $\Delta g \approx 0.2\ \hbar$ (bag model)

...

around/after 2000: several DIS fits: Δg largely unconstrained

GRSV, BB, AAC, ...

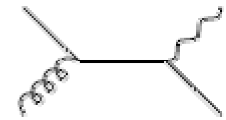
now

$\Delta g(x)$ is not large and positive at $x \simeq 0.05 \div 0.2$; still a long way for full moment $\int \Delta g\, dx$ but anomaly scenario (2-4 units of $\hbar$) excluded

PHENIX, STAR, HERMES, COMPASS

time

RHIC/RHIC-II 500 GeV collisions (smaller x), more luminosity (rare probes)

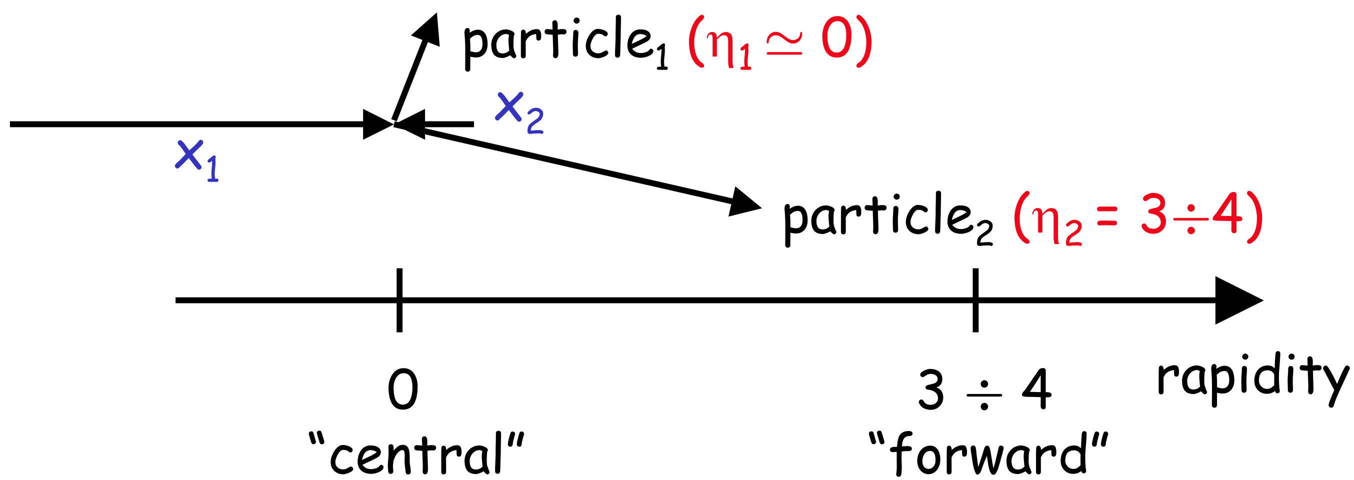
prompt photons: rare, but clear probe of sign through 

heavy flavors: mass allows (?) pQCD at small $p_T \rightarrow$ probes smaller x

particle correlations: better control of kinematics = x-range *and* sign

idea:
forward-central
correlations

$\boxed{x_1 \gg x_2}$



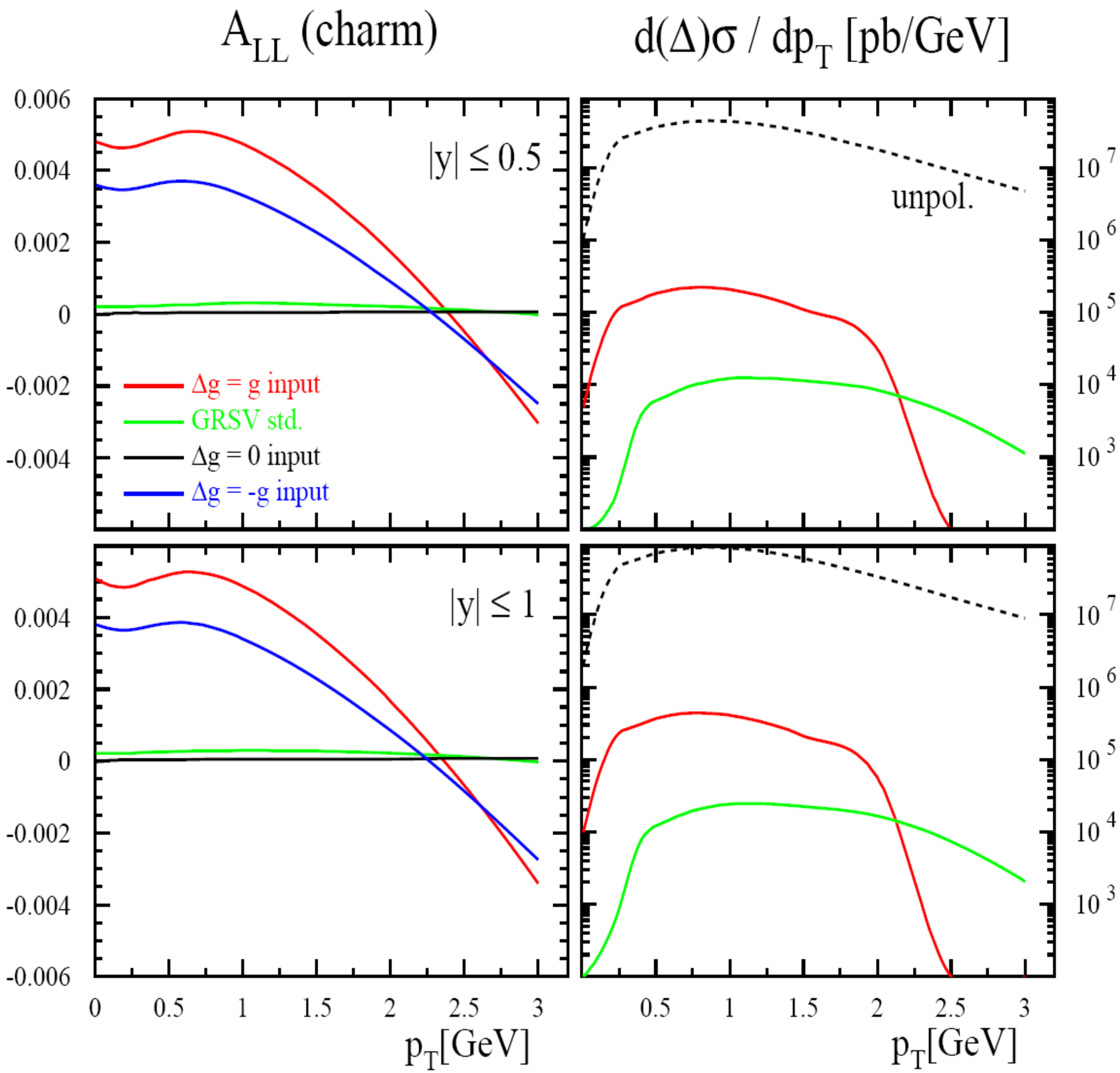
strongly asym. kinematics: $x_1 \gg x_2$

$\rightarrow$ qg-scattering $q(x_1)\, g(x_2)$ important

NLO 2-hadrons just completed & pheno. studies under way:
Jäger, Owens, MS, Vogelsang

"quick & dirty study"
J. Riedl, MS

■ heavy flavors (prospects for near future)



gg scattering dominant
→ sign of Δg is an issue

A_{LL} very small

charm detection ($c \rightarrow \mu$, …)
not yet included

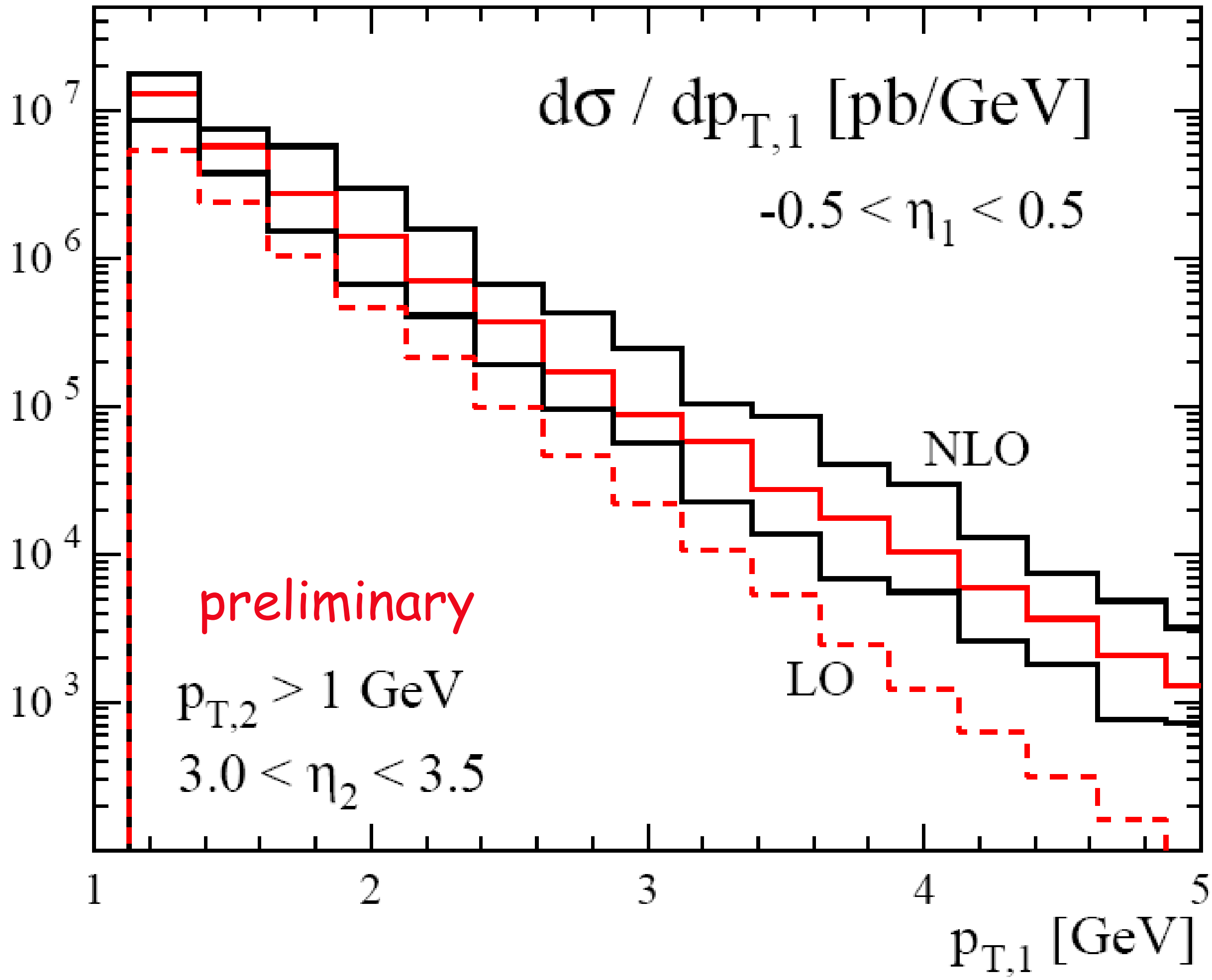
pQCD at work?

stay tuned for
- heavy quark correlations
- charge asymmetry

unpolarized "benchmark" for 2-hadrons

Jäger, Owens, MS, Vogelsang

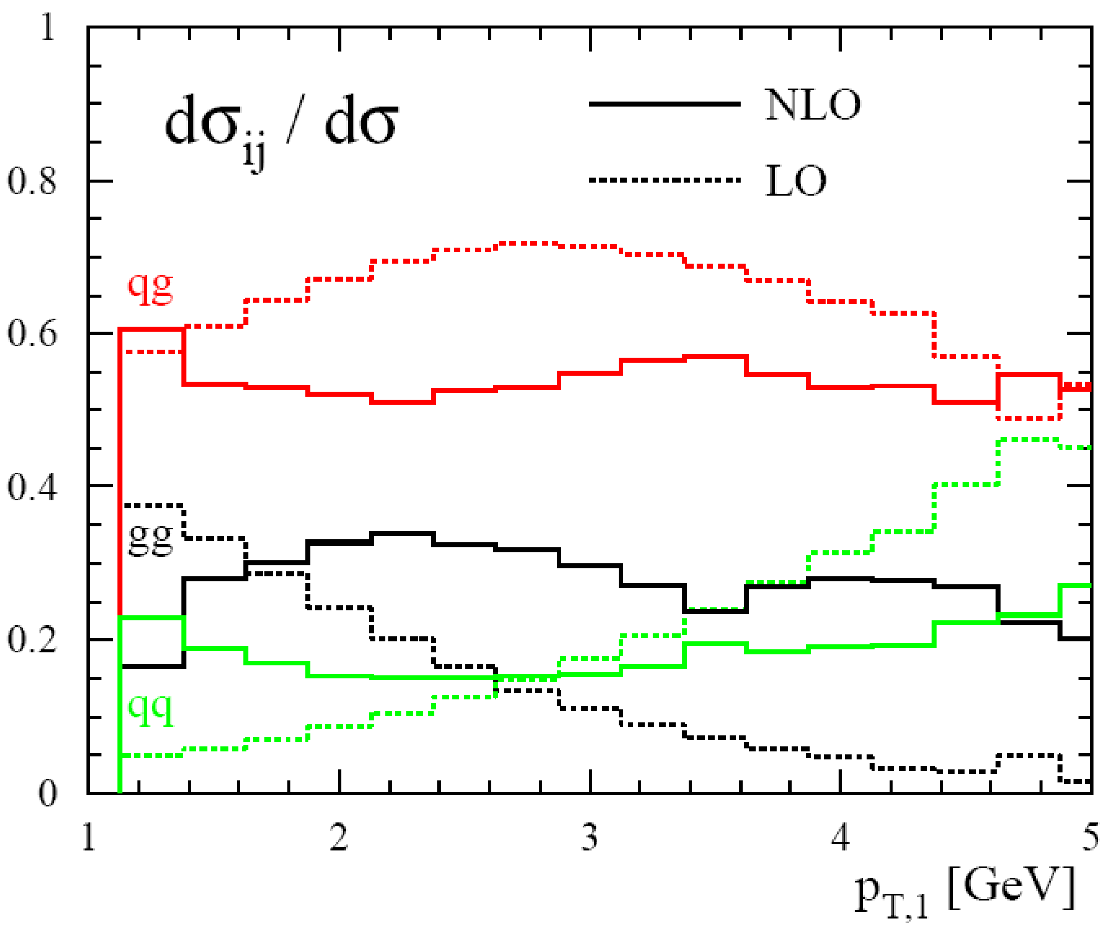
→ confidence in A_{LL} measurements & interpretation

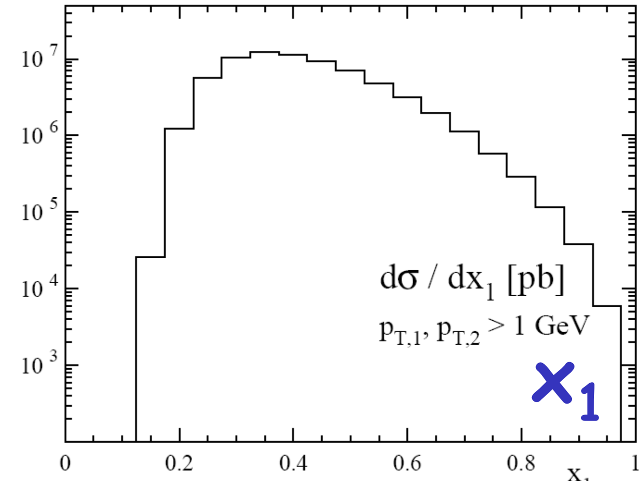


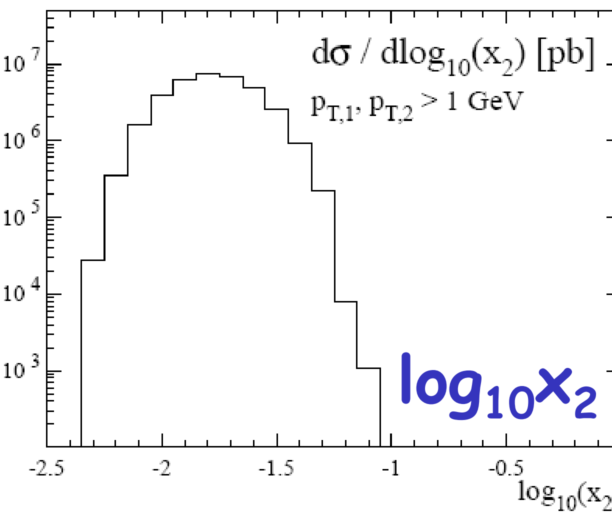
"scan" in p_T of central hadron

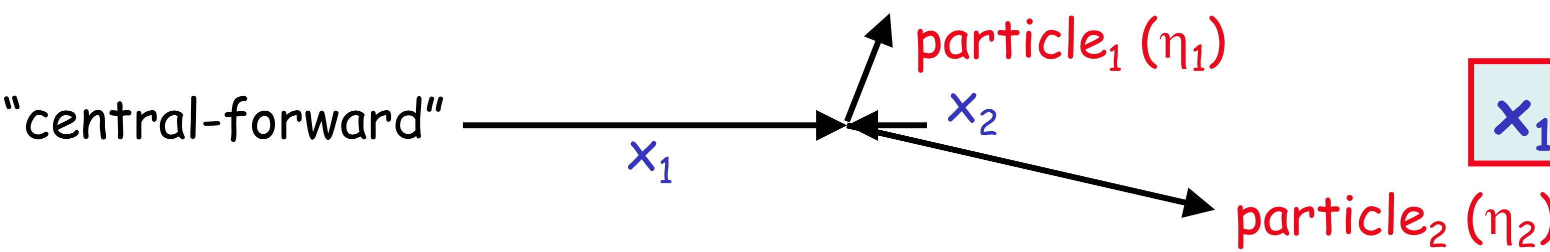
- never measured at collider energies
  → test of QCD factorization
- doable both at STAR and PHENIX
- NLO corrections & scale dependence are substantial

kinematics is as expected:





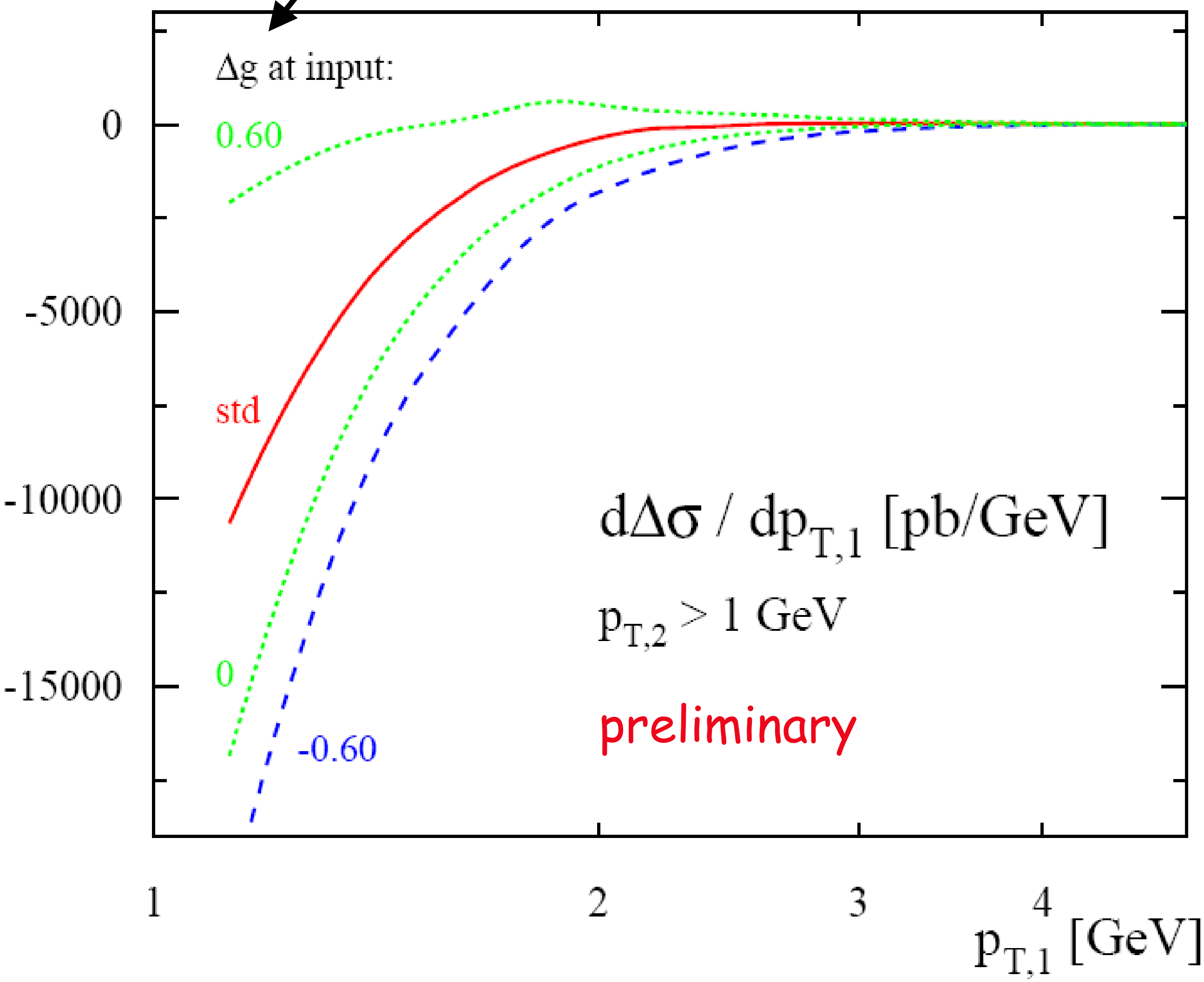




$x_1 \gg x_2$

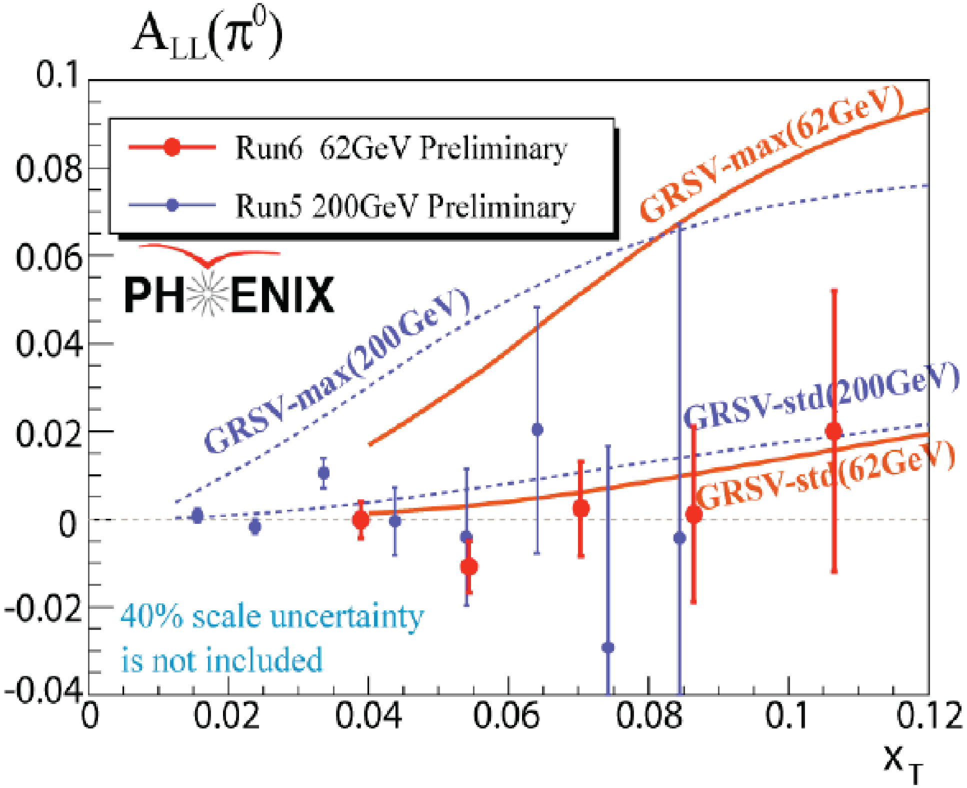
→ sensitivity to Δg (sign!)

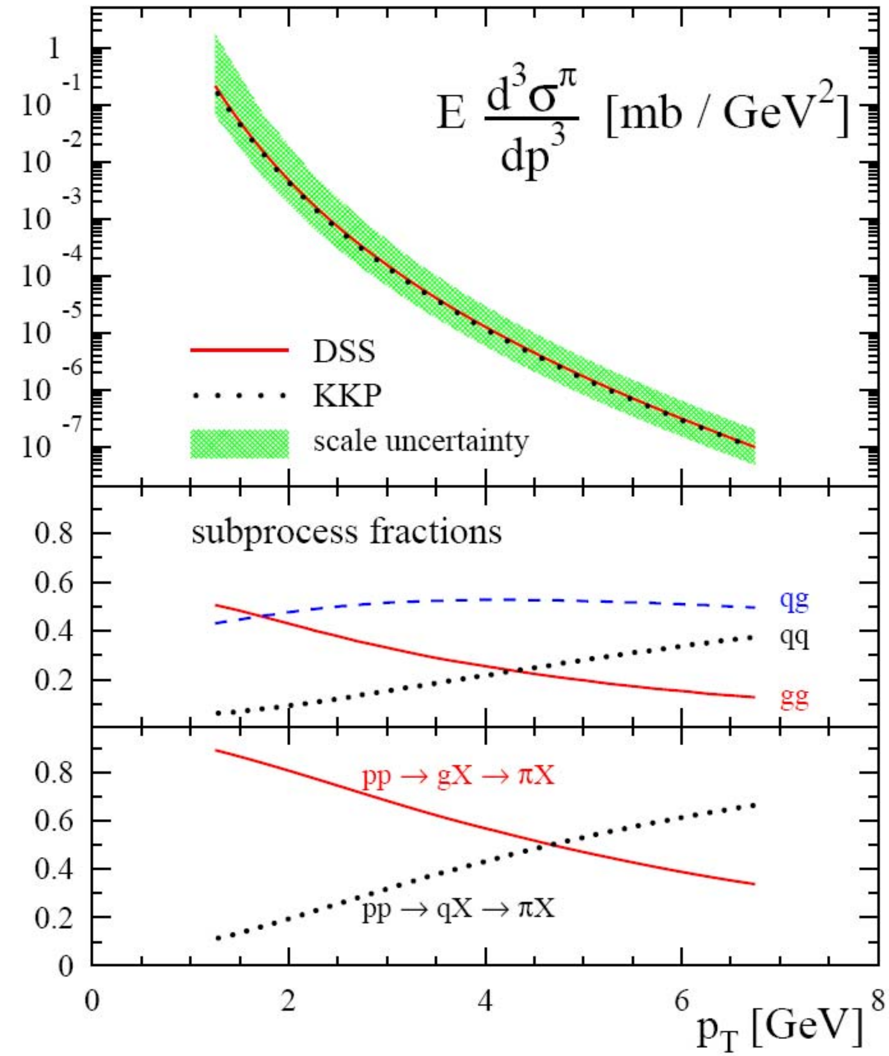
1st moment *assumed* at input scale



- qg-fraction strongly depends on Δg
- NLO corrections large, in particular, for small "std-like" Δg
- expected A_{LL}'s are only a few $\times 10^{-3}$

new kid on the block: 62.4 GeV data



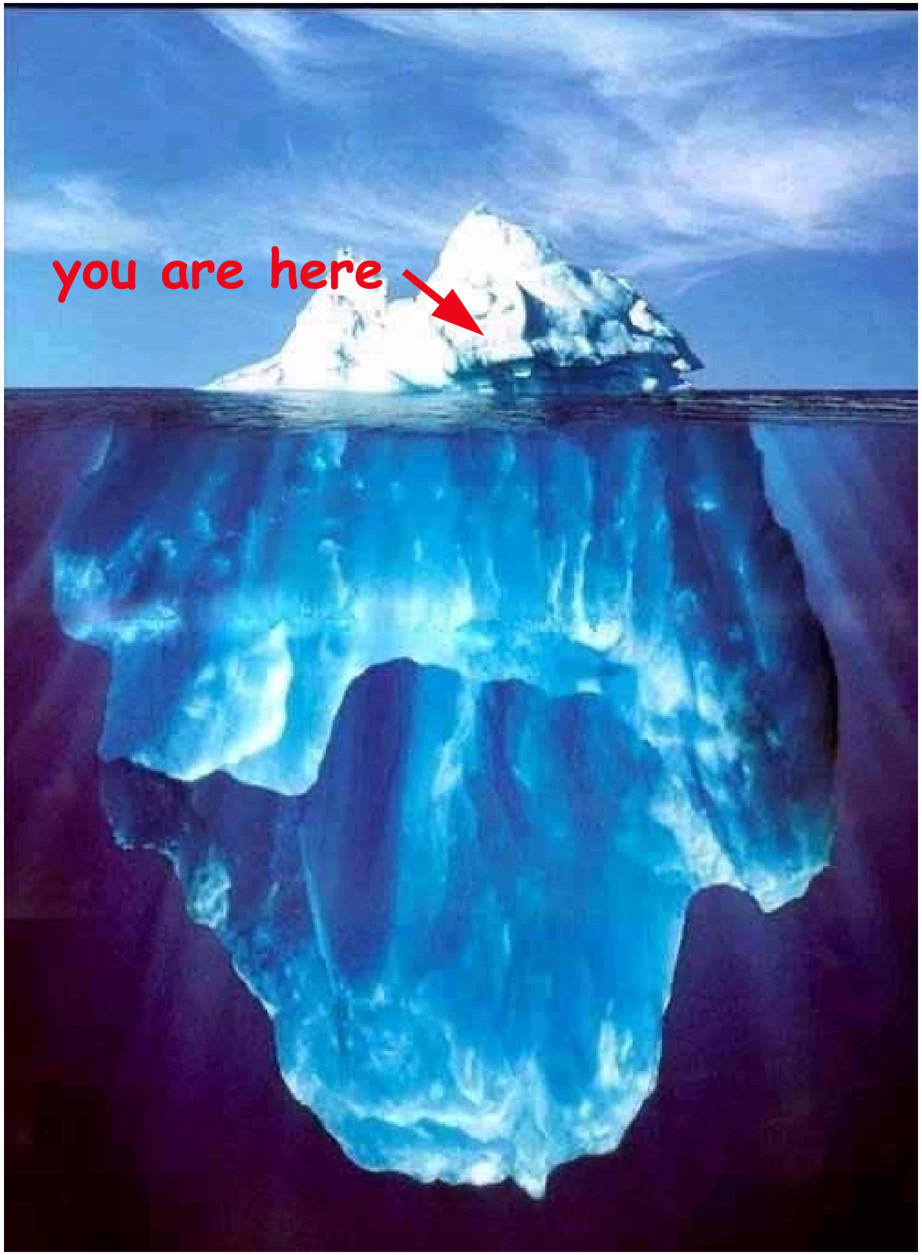


- explores larger x values
- pQCD at the edge ?
  → testing ground for resummations
- qg scattering more relevant → sign!

could be interesting/important to collect more data at 62 GeV

conclusions

we have just explored the tip of the iceberg



many avenues for further important measurements and theoretical developments